CHANGES IN THE VERTICAL MASS DISTRIBUTION IN THE VICINITY OF THE RAPIDLY DEEPENING LOW OF MARCH 24–26, 1954

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INTRODUCTION

Weather forecasters frequently miss sudden changes in the intensity of Lows and Highs, and even more frequently miss rapid changes of pressure not associated with the centers of systems. The complex combination of circumstances which results in pressure change is only partially understood in the best of situations, and most forecasters still rely heavily on simple extrapolation of the past movement and intensity of systems and their changes for the construction of prognostic pressure fields. Attempts to forecast major changes in these properties, while frequently successful, have rarely been based on complete understanding of the processes involved. A case history such as this cannot possibly close the gaps in the basic understanding of pressure changes, but it will attempt to record for whatever purpose it may be useful, the change in mass, at least, about a rapidly deepening Low, and to deduce therefrom an instructive, though admittedly incomplete, explanation of the deepening.

BACKGROUND

Explanations of large pressure changes, including the change of intensity of systems, fall generally in two categories. What Austin [1, 2] calls the thermal theory attributes the change of pressure to the change of density in the air column over the point of measurement. Density being inversely proportional to the temperature, warming or cooling within this air column will, according to this theory, produce falling or rising pressures, respectively, at the base of the column. Theoretical support for this is found in the hydrostatic equation. The mechanisms by which such temperature changes may occur are many, but the one considered most capable of rapidly producing large changes in the troposphere is the advection process by which air masses or layers having different temperatures are moved through the sides of the column by the existing wind. Other temperature changes are possible as a result of adiabatic processes of lifting or sinking, or by nonadiabatic processes such as radiational cooling in cold anticyclones and surface heating in warm or thermal Lows. The release of latent heat also affects the density and may be a source of pressure change. It is generally agreed, however, that these latter processes normally result in relatively small changes, and that advection, alone of the thermal processes, can be responsible for large changes. This approach leaves unanswered, questions as to the source of warm or cold air, what initiates the advection, and why the particular wind fields develop. If thermal theories provide adequate explanation of barotropic pressure changes in the troposphere, the cause of the changes must frequently be found in the upper stratosphere, or less than one-fifth of the atmosphere where the data are insufficient to provide decisive answers.

A second approach is based on the accumulation and depletion of air due to the wind field and may be called the dynamic approach. Pressure variations are considered in this case to be due to convergent or divergent flow, or to the vorticity of the upper flow. These produce changes in the mass of vertical air columns by differences between the inflow and outflow of the columns, resulting in either adiabatic changes in temperature or changes in the vertical extent of the atmosphere, or both. Bjerknes [3] explains the pressure falls ahead of a cyclone by the excess of divergence aloft over convergence near the surface, and the rises to the rear by the reverse distribution. Deepening of a Low would then occur when, over the surface center, the balance between the two processes became tipped in favor of the divergence. The Bjerknes model permits, but does not require, aid from the advection and other thermal processes. Several rules have evolved for predicting the deepening and filling of systems, based on the shape of the upper level streamlines.[1] Application of the various theories comprising the dynamic approach frequently runs into difficulties due to the wide separation of reporting stations and the inaccuracies of wind measurements.

Of these approaches, the advection concept is the one now most frequently used by forecasters, largely because

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[1] Schmidt [4] has summarized some of these rules as follows;

a. If the high level isobars diverge uniformly (i. e., the distribution of gradient across stream remains the same, changing only in strength and/or direction along the stream), surface pressure falls (rises) if the largest gradients lie on the high- (low-) pressure side.

b. If the high-level isobars converge uniformly, surface pressure rises (falls) if the largest gradients lie on the high- (low-) pressure side.

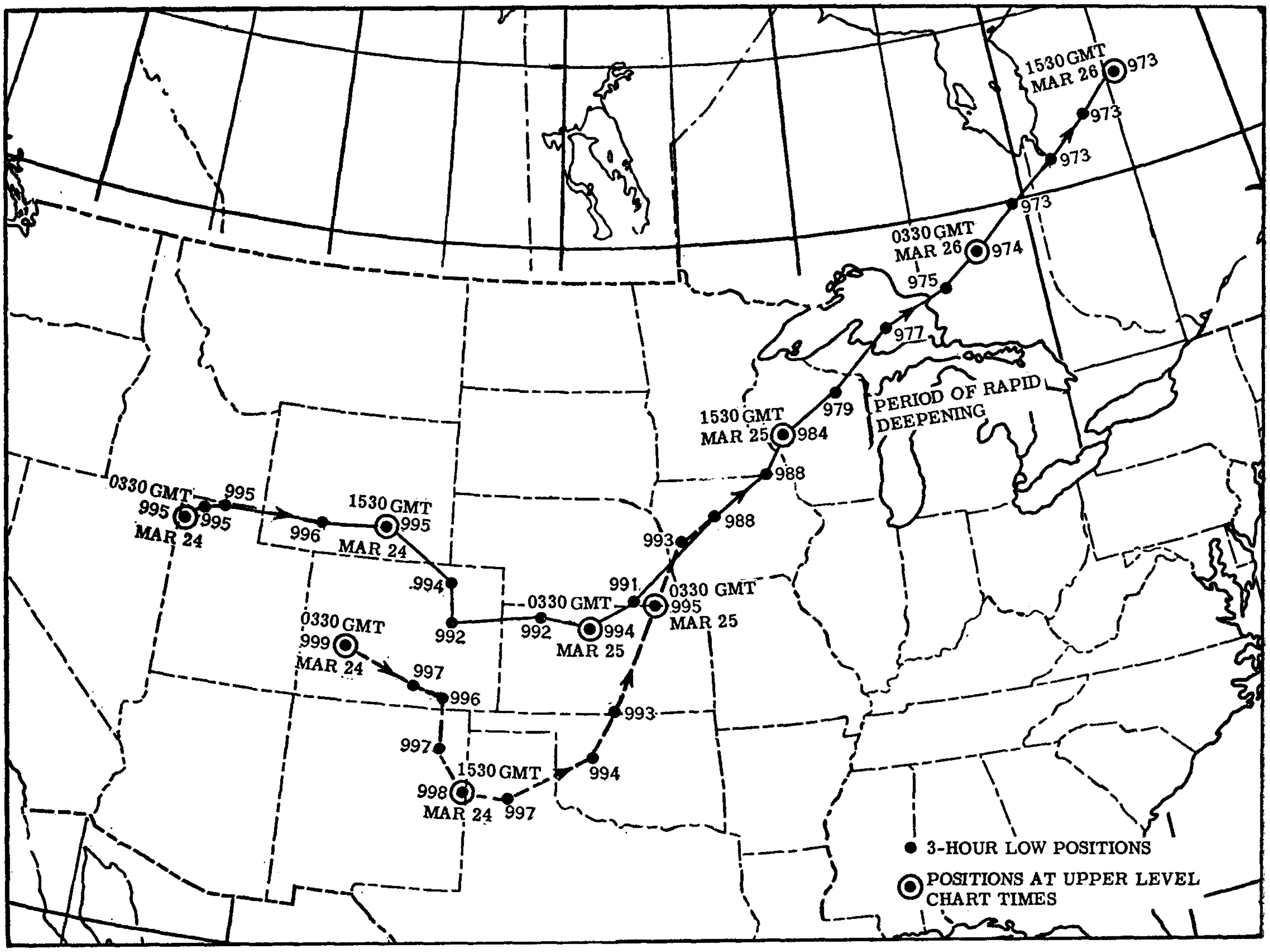

FIGURE 1.—The sea level track and central pressures of the deepening Low of March 24–26, 1954.

the thermal pattern is more easily derived and represented than are convergence-divergence or vorticity patterns. However, the use of vorticity patterns has increased in recent years. Fjørtoft[5] has developed a technique which may be used in the average forecasting center, for deriving graphically a "space mean" or smoothed flow pattern, with isopleths of vorticity as the difference between the smoothed flow and the actual flow, and he suggests a way of constructing prognostic upper air charts by moving the centers of vorticity along the mean flow, then subtracting the new vorticity from the mean flow to get the prognostic contours.

Vederman[6] studied the changes in mass between the standard raob levels over the centers of 25 rapidly deepening Lows, showing that the greatest depletion of mass in this type of system normally appears above the 200-mb. surface. The method employed by Vederman has been used in the current study, and extended to show the changes in mass out to about 350 miles from the center.

DEVELOPMENTS PRIOR TO DEEPENING

The Low of March 24–26, 1954, was selected for study because of its rapid deepening—20 mb. in 24 hours and 9 mb. in a 6-hour period (fig. 1)—and because its development apparently contributed toward a polar outbreak which spread record-breaking low temperatures into the North Central States. Its early history was quite similar to that of a Low which occurred only a week earlier but which did not deepen. Both Lows formed with about the same depth over Nevada and in association with the eastward drift of pockets of cold air which had become cut off from the polar cold source. Both moved eastward with little change of intensity as far as Kansas, but differences appeared in the surrounding atmosphere to change the subsequent course and development of the second Low. A blocking action which had just begun to be effective over northwestern Canada with the earlier cold pocket became much more pronounced and had retro-

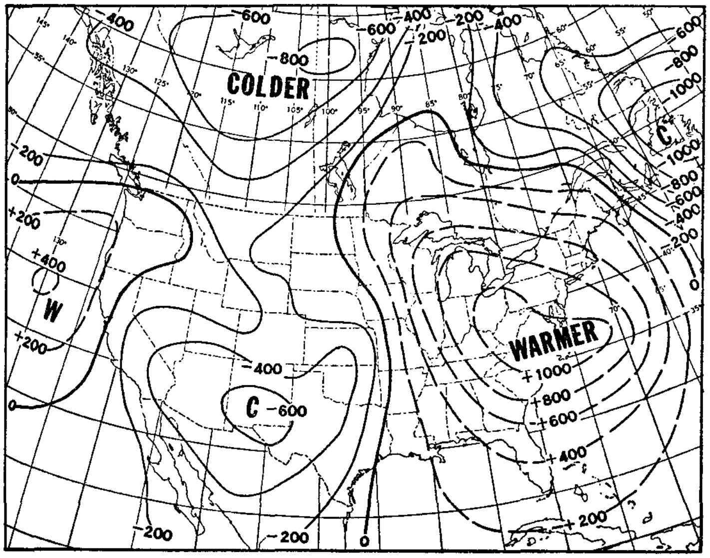

FIGURE 2.—The total change of thickness between the 1,000- and 500-mb. surfaces during the 3-day period March 22-25, 1954, showing the strong warming which occurred over eastern United States preceding cyclogenesis.

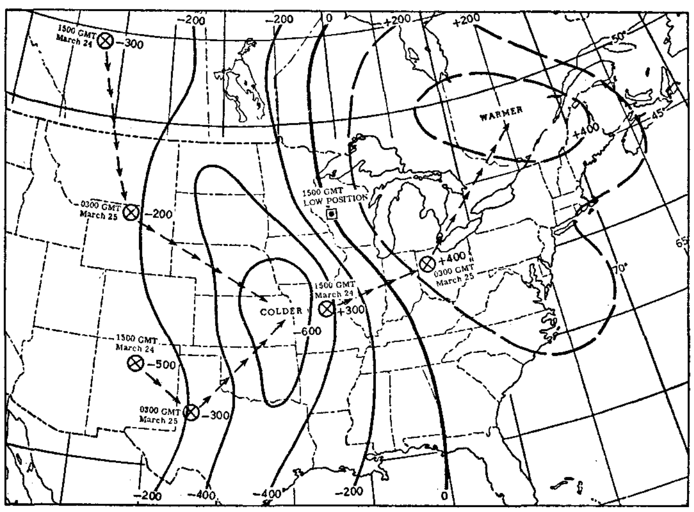

FIGURE 3.—The 12-hour thickness change during the first part of the period of deepening, and the past positions of the change centers, showing juncture of cold advection centers.

gressed westward to the eastern Pacific by the time of the second cutoff cold pool. The eastern United States was flooded with cold air prior to the first Low, but 3 days of strong warming (fig. 2) preceded the second, so that while the earlier Low was carried generally eastward from northern Nevada to New York, reaching a minimum central pressure of 988 mb. over Kansas and filling for 12 hours thereafter, the later one took a more northerly course around the warm air and deepened rapidly, as indicated in figure 1. The southern (dashed) track in this figure belongs to a secondary pressure minimum which preceded the main Low across the Plateau and attached itself to the polar front which lay across central Texas. A frontal wave formed (fig. 4), the warm sector of which contained the warmest air thus far of the spring season.

Meanwhile, the cold pocket had moved inland to the Plateau region, accompanied by a weak short-wave upper trough, figure 5. The long-wave trough remained just west of the California coast, where it was re-deepened by a new surge of cold air from the north. The newest cold outbreak also provided the energy necessary to displace the Arctic front southward from its quasi-stationary position through Montana and southern Manitoba. Figure 3 shows, by means of the 12-hour thickness change between the 1000- and 500-mb. surfaces, the progress of the Arctic air along the east side of the Continental Divide. The momentum of this air, extending up to 500 mb. as evidenced by the increased northwesterly flow bridging over the Pacific coast trough, was added to that of the cold air mass from the Plateau to displace a large amount of warm air from the Western Plains between 0300 GMT and 1500 GMT on the 25th. An unusually strong solenoidal field was produced across Kansas and Nebraska with the proximity of Arctic and tropical air masses, so that the superposition of the cyclonic vorticity of the upper level trough completed the conditions customarily considered necessary for strong cyclogenesis.

Significant deepening had not been predicted until early on the 25th, but the Prognostic Discussion issued by the WBAN Analysis Center with the prognostic chart based on the 0630 GMT data read in part: "The outstanding feature of the surface chart is the deep low over central United States. The advection of warm air and vorticity and Palmer's objective technique [7] indicate rapid northeastward motion of this storm. Marked deepening of this storm is expected as it moves under much lower heights aloft."

DEVELOPMENTS DURING AND FOLLOWING DEEPENING

Deepening occurred in steps, the central pressure falling from 994 mb. at 0330 GMT on the 25th to 988 mb. 6 hours later, leveling, then plunging 9 mb. in 6 more hours to 979 mb. at 1830 GMT. The 1500 GMT raobs were taken in the middle of the period of most rapid deepening. The height of the closed circulation did not change appreciably from just under 300 mb. during the deepening process, although the number of closed sea level isobars increased by nine (27 mb.).

The wave on the polar front developed rapidly, with severe thunderstorms and a few tornadoes occurring along the cold front from the Texas Panhandle to eastern Kansas on the 24th and thence through Missouri and Illinois on the 25th as the wave occluded. Maximum vertical instability occurred near the point of occlusion, although some squall activity moved out along the warm front. Heavy rainfall amounting in some localities to over 4 inches spread in a relatively narrow band across northern Missouri, southeastern Iowa, northern Illinois, Indiana, and Ohio, and southern Michigan. Some of the areas affected had previously been in serious drought. The rain just missed other areas which continued dry.

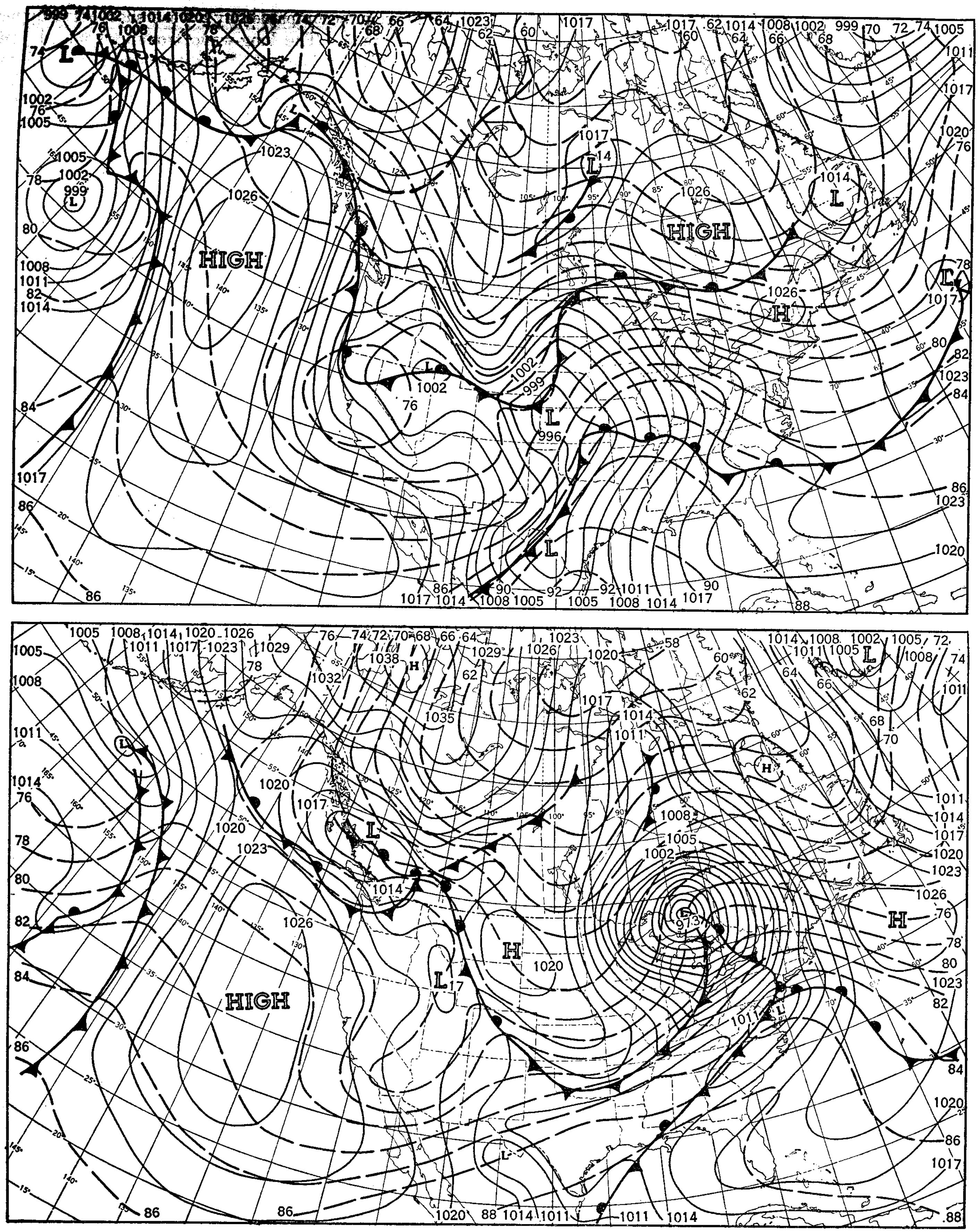

FIGURE 4.—Sea level charts just before (0030 GMT, March 25, top) and just after deepening (0030 GMT, March 26, bottom) with 1,000–500-mb. thickness lines (dashed) from upper air data 3 hours later, showing the near approach of Arctic and tropical air masses, strengthening thermal gradient, and subsequent deepening.

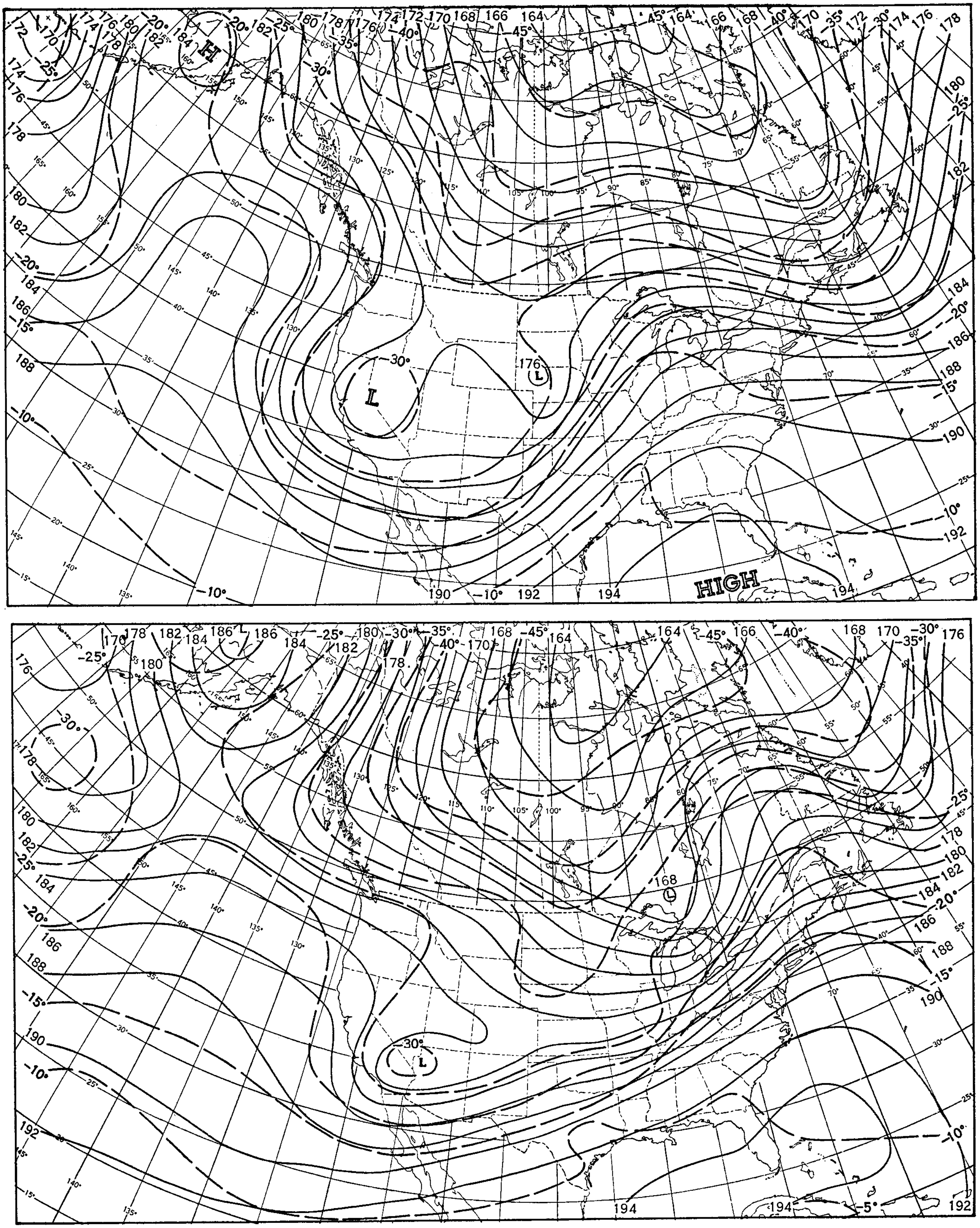

FIGURE 5.—500-mb. contours and isotherms (dashed) just before (0300 GMT, March 25, top) and just after deepening (0300 GMT, March 26, bottom). Note the blocking ridge in the eastern Pacific and the cold Low over California.

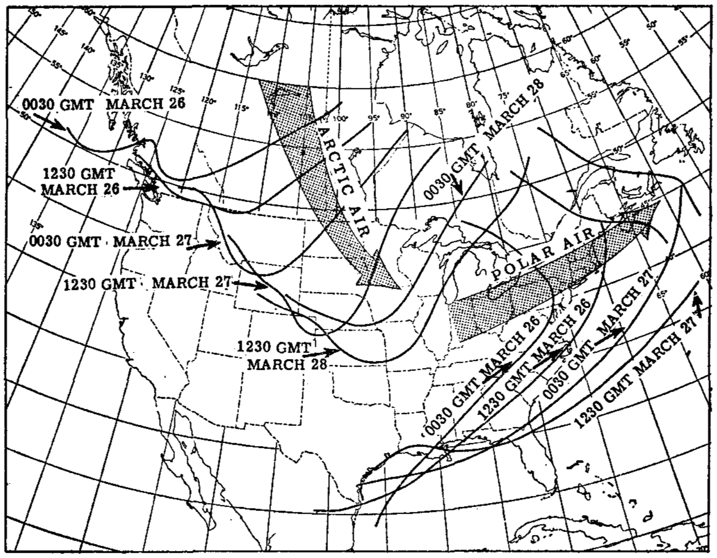

FIGURE 6.—Successive positions of the polar front after the maturity of the cyclone, and the simultaneous advance southward of the new Arctic front.

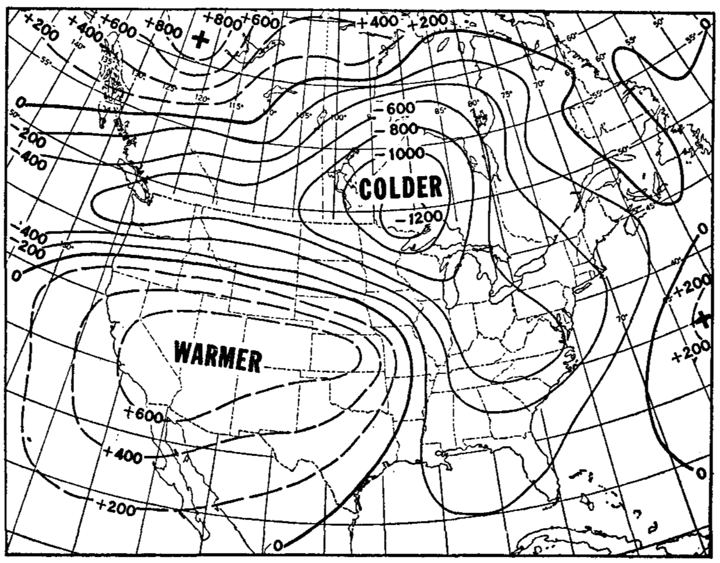

FIGURE 7.—The total change of thickness between the 1,000- and 500-mb. surfaces during the 3-day period March 25–28, 1954, showing the strong cooling which followed the cyclone.

The surface center continued to move northeastward, coming under the closed upper Low which had been in the Hudson Bay region for several days. The cyclonic circulation in the lower troposphere over this area was thus markedly strengthened, and the resulting northerly current over western Canada was in a large measure responsible, together with the persistence of the blocking ridge in the eastern Pacific, for the southward transport of the abnormally cold air mass (fig. 6) which had been forming over the Yukon Territory and Alaska. Although some of it moved southwestward into the Pacific, a large portion of this cold air spread southeastward into northern and eastern United States (fig. 7). Minimum temperature records for the date were established in northern Minnesota, International Falls recording −5° F. on the 28th, −5° F. on the 29th, and −11° F. on the 30th.

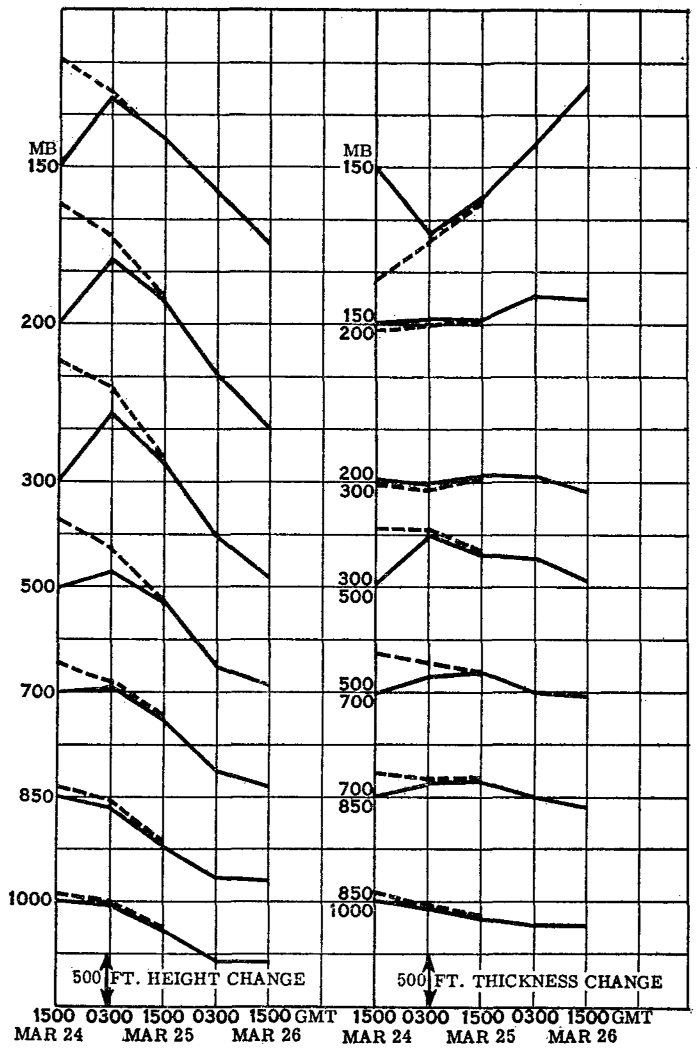

FIGURE 8.—Changes in the heigths (left) and thicknesses (right) at and between standard pressure surfaces directly over the sea level low center. The solid lines refer to the original Low, the dashed lines to the wave on the polar front prior to their merger.

DISCUSSION OF MASS CHANGES

Graphical subtraction of successive levels of carefully reanalyzed constant pressure charts produced thickness isopleths for all layers up to 150 mb. for the three raob times representing the period of rapid deepening. The changes in thickness over the moving Low center were determined for the two 12-hour periods and the overall 24-hour period of deepening, and are shown in figure 8. These agree well with Vederman's results. The thickness charts were subtracted graphically to get the 12-hour and 24-hour change over the area around the surface Low (fig. 9). This was done with the surface Low positions superimposed so that the coordinates of the changes are related to the Low rather than to the surface over which it was moving. The direction of motion of the Low was not far from 45° east of north through the period. The top squares in figure 9 and the top right graph in figure 8 are the height changes of the 150-mb. surface with the sign reversed. These might be interpreted as the

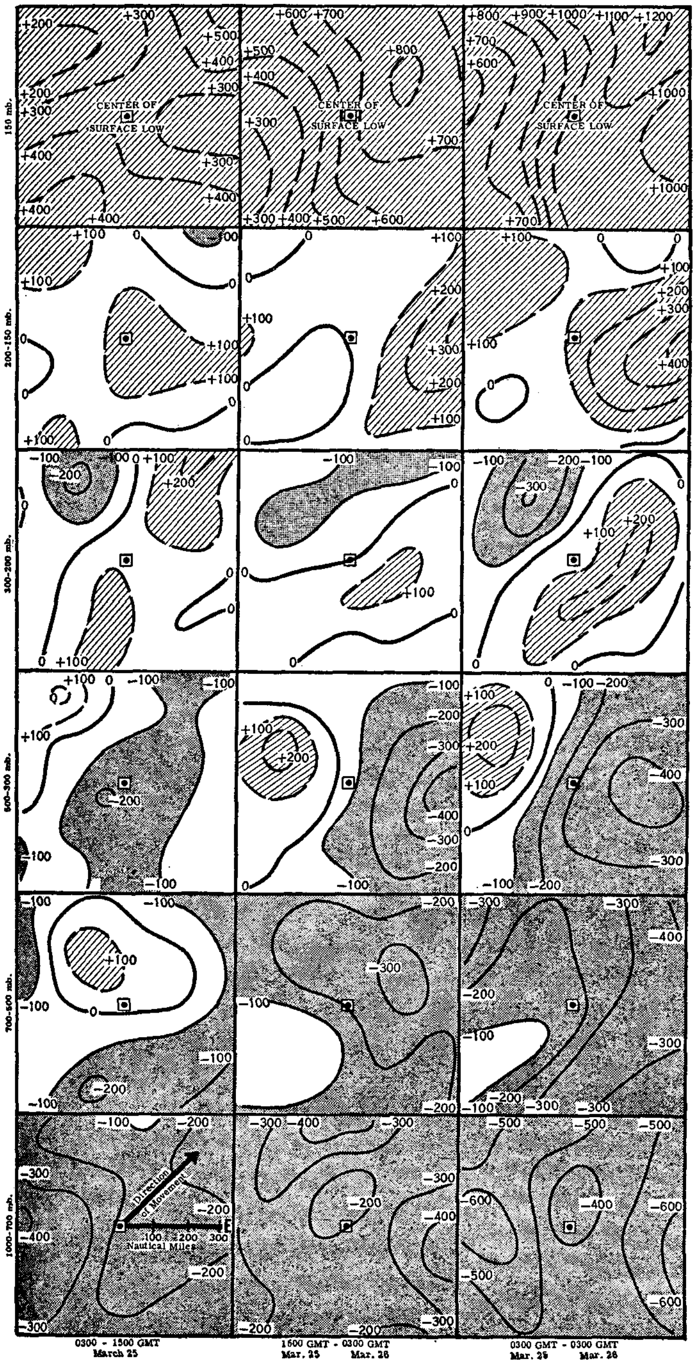

FIGURE 9.—Changes in the thickness between indicated mandatory pressure surfaces, computed relative to the moving sea level Low center, showing the distribution of warming and cooling in the vicinity of the lowest pressure.

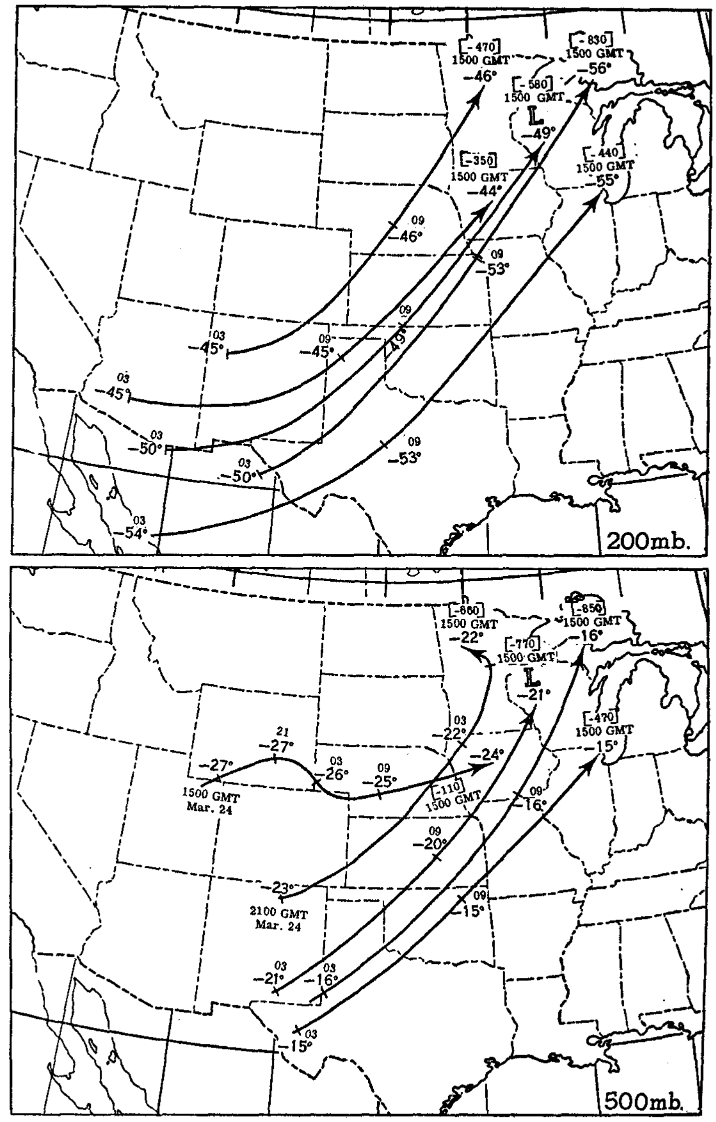

FIGURE 10.—Trajectories of air particles into the vicinity of the Low, showing differences in source, speed, and temperature of air arriving over the Low at time of rapid deepening. 12-hour changes in trajectory altitude (ft.) are shown in brackets.

thickness changes between the 150-mb. surface and some very high fixed surface near the top of the atmosphere.

These charts show general cooling relative to the Low below the 700-mb. surface within at least 350 miles of the center throughout the period of deepening, although individual stations in advance of the Low reported warming. This is in agreement with our concept of the occlusion process, in which cold air surrounds the Low in the lower levels, the warm air being lifted and the cold air becoming deeper with time. Fleagle [8] in similar cases attributes at least part of the cooling in the lower levels to upward motion. The strong cooling observed to the east of the Low up to 300 mb. in the second period was almost certainly due to upward motion from the convergent lower levels to the divergent flow near the tropopause, which was near 200 mb. in that quadrant. The strong warming above the 200-mb. surface in the northeast quadrant was probably advected, as shown hereafter, rather than adiabatic warming of air descending to the level of maximum divergence. Note that, relative to the Low, the advection of cold air in the southwest quadrant was not greater than the cooling in other quadrants during the second period, although individual stations in that area were the ones to feel the influx of cold air behind the cold front. Warming from 700 to 300 mb. continued in the northwest quadrant of the Low as it moved under a relatively stagnant pool of warm air over the Dakotas (see fig. 5 and the 500-mb. chart for 0300 GMT on the 25th). Individual stations in this pool showed slow cooling, which perhaps is more consistent with the weakly convergent flow. The effect of the warming would be toward less mass and lower surface pressures in that quadrant, if not compensated for at other levels. The warming occurred only in the higher layer during the second 12-hour period, as the occlusion progressed.

The otherwise decreasing thicknesses around and over the Low from 1,000 mb. up to 300 mb. in themselves represent increasing mass and would have contributed to filling rather than deepening, except that the height of the 300-mb. surface fell during the same period at a rate almost enough greater than the 1,000-mb. rate to make up for the cooling. Two explanations are perhaps possible for why the 300-mb. and other higher level surfaces fell so rapidly. One suggests that warmer and thicker air was advected into the layer over these surfaces thereby lowering them, some much higher surface remaining at constant height. The other suggests that depletion of mass below these surfaces permitted them and all higher pressure surfaces to fall.

In checking the first of these possibilities, it may be observed that the thickness between 200 and 150 mb. increased a little. The changes in specific higher layers could not be checked with the sparse coverage of data. Trajectories (fig. 10) were constructed on the 200-mb. surface to see if the warm air were advected or formed by subsidence. The recent paths were traced of particles arriving in the northwest, northeast, southwest, and southeast quadrants and over the surface center at the time of maximum deepening. The majority of the trajectories show moderate conservatism of temperature (and potential temperature) suggesting that thermal advection was indeed operating, temperatures over the Low having been colder prior to this time. If subsidence had occurred the constant pressure trajectories would have warmed with time. However, this warmer air did move downslope in coming over the Low, the amount of height change in 12 hours of trajectory being indicated in brackets at the trajectory endpoints. The 200-mb. trajectory fall was about equal to the fall in height of that surface over the Low center for the same period, so that it appears that whether or not the advection produced the sinking of the isobaric surfaces, it was at least associated with it. The presence of divergence ahead of the Low having already been indicated, we must assume that in this case both processes were involved in the deepening. Trajectories were constructed also on the 500-mb. surface to show differences in the transport at that level. The same conservatism of temperature was evident at the lower level.

It may be instructive to consider the trajectories of figure 10 from other aspects. The one entering the northeast quadrant of the Low at 200 mb. is interesting in that it shows cooling. This may have been a result of some upward motion through the 200-mb. surface, perhaps associated with the divergence aloft in that quadrant and preceding the advection of less dense air. The trajectory entering the southwest quadrant at 500 mb. shows warming, due to subsidence downward through the 500-mb. surface, of air coming off the Plateau toward the Plains and then moving over an air mass which was divergent in the lower levels.

CONCLUSIONS

1. Both the thermal and the dynamic approach to pressure change may be applied successfully, at least in a qualitative sense, to explain the deepening of this Low.
2. The cooling around the center of this storm with the occlusion of its fronts resulted in an increase in mass of air per unit height from the surface up to near the tropopause, in conformity with the Bjerknes cyclone model.
3. The contribution of increased temperature to mass decrease in the region above the tropopause, while not measurable through a very thick layer due to observational limitations, appears in this case to compensate at least partially for the increase in mass in the troposphere.
4. In this case the evidence suggests the advection of the warmer stratosphere mentioned in 2, as against its formation by subsidence.

ACKNOWLEDGMENTS

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REFERENCES

1. J. M. Austin, "Mechanism of Pressure Change", *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 630–638.
2. J. M. Austin, "Temperature Advection and Pressure Changes", *Journal of Meteorology*, vol. 6, No. 5, Oct. 1949, pp. 358–360.
3. J. Bjerknes, "Extratropical Cyclones", *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 577–598.
4. F. H. Schmidt, "On the Causes of Pressure Variations at the Ground", *Mededeelingen en Verhandelingen*, Nederlandsch Meteorologisch Instituut, Ser. B, Deel 1, Nr. 4, 1946, pp. 1–37.
5. R. Fjørtoft, "On a Numerical Method of Integrating the Barotropic Vorticity Equation", *Tellus*, vol. 4, No. 3, Aug. 1952, pp. 179–194.
6. J. Vederman, "Changes in Vertical Mass Distribution Over Rapidly Deepening Lows", *Bulletin of the American Meteorological Society*, vol. 30, No. 9, Nov. 1949, pp. 303–309.

7. W. C. Palmer, "On Forecasting the Direction of Movement of Winter Cyclones", *Monthly Weather Review*, vol. 76, No. 9, Sept. 1948, pp. 181–201.

8. R. G. Fleagle, "The Fields of Temperature, Pressure, and Three-Dimensional Motion in Selected Weather Situations", *Journal of Meteorology*, vol. 4, No. 6, Dec. 1947, pp. 165–185.

CORRECTION

MONTHLY WEATHER REVIEW, vol. 82, No. 2, Feb. 1954, page 60: In paragraph 1, sentence 3 should read, "For the country as a whole the weighted temperature average was higher than for any *previous* February in the *62-year* period of record."

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